PERFORMANCE OF CARDIOVASCULAR FLUID-STRUCTURE INTERACTION SIMULATIONS USING SUB-CYCLING

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Introduction

The interaction between the blood flow and the distensible vessel walls gives rise to complex fluid-structure interaction (FSI) problems. The time scales associated with the flow and the structural problem in FSI simulations can be very different. For example, the simulation of turbulent blood flow in the vicinity of the aortic valves or a severely stenosed artery, requires the use of small time step sizes to resolve the flow field in time, whereas the time scale associated with the vibration of the structure generally will be much larger.

Adapting the time step size to the smallest required time scale would increase the computational time and in case of a strongly partitioned approach, the number of coupling iterations. Hence, appropriate sub-cycling procedures within the individual sub-problems need to be devised. However, coupling different time step sizes for the flow (Δt_f) and the structural problem (Δt_s) can affect the temporal stability of the simulation, providing an additional challenge for the development of these sub-cycling procedures.

In this study, cardiovascular FSI simulations using sub-cycling are devised and their stability and accuracy are analyzed.

Methods

First, an analytical study is performed in which the temporal stability of the one dimensional flow in a straight, flexible artery is studied. In this analysis the time step size of one sub-domain is considered to be *k* times the time step size of the other sub-domain with *k* a positive integer. For *k >1* the effect of 'sub-cycling' on the stability behaviour is studied.

To verify the analytical results and to study the accuracy of sub-cycling, a numerical study is performed in which the propagation of a flow wave in an artery is simulated. The equations for the blood flow and the deformation of the vessel wall are solved with ANSYS Fluent and ABAQUS/Standard resp., which are strongly coupled with the IQN-ILS technique [Degroote, 2009].

Results

Stability is demonstrated (both analytically and numerically) for the simulations using sub-cycling in the fluid problem. Sub-cycling in the structural domain, however, results in an unstable behaviour.

In Figure 1 the inlet pressure, obtained using a simulation with sub-cycling in the fluid domain ($\Delta t_f = \Delta t_s/10 = 10^{-4}$ s; red curve) is compared to the inlet pressure of two simulations in which the time step size of the structural problem is adapted to the time step size of the flow problem ($\Delta t = 10^{-3}$ s; black and $\Delta t = 10^{-4}$ s; blue curve). The simulation with sub-cycling accurately resolves the high frequency components present at the start of the simulation. Yet, the calculation time is decreased by a factor 5, compared to the simulation for which $\Delta t_f = \Delta t_s = 10^{-4}$ s.

The sub-cycling procedure has successfully been applied to a more complex FSI simulation of the blood flow in a patient-specific aortic arch.

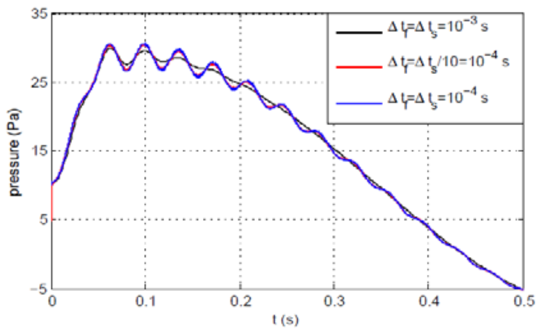

Figure 1: Influence of $\Delta t_f / \Delta t_s$ on the evolution of the inlet pressure.

Discussion

Compared to an FSI simulation for which the specified time step is adapted to the smallest required time scale, sub-cycling in the fluid significantly speeds up the calculation without loss in accuracy.

References

J. Degroote *et al*, Computers and Structures, 87:793-801, 2009.